

# **Strongly-Interacting Ultracold Atoms**

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Support

DOE, Division of High Energy Physics  
DOE, Division of Basic Energy Sciences

# Ultracold Atoms

Ultracold: much lower temperature  
than natural low-energy scale  
set by interatomic potential

natural low-energy scale:  $\hbar^2/(m r_{\text{int}}^2)$

typical mass:  $m \sim 10 - 100 m_p$

typical range\*:  $r_{\text{int}} \sim 10 - 100 a_0$

Ultracold:  $T \ll 10^{-4} - 10^{-1} \text{ K}$

$T \ll 10^{-9} - 10^{-6} \text{ eV}$

\*relevant range:  $r_{\text{int}} \sim (m C_6 / \hbar^2)^{1/4}$ ,  
where  $C_6$  is coefficient in van der Waals potential:  $V(r) \longrightarrow -C_6/r^6$

## Ultracold atoms (cont.)

### Technology for ultracold atoms

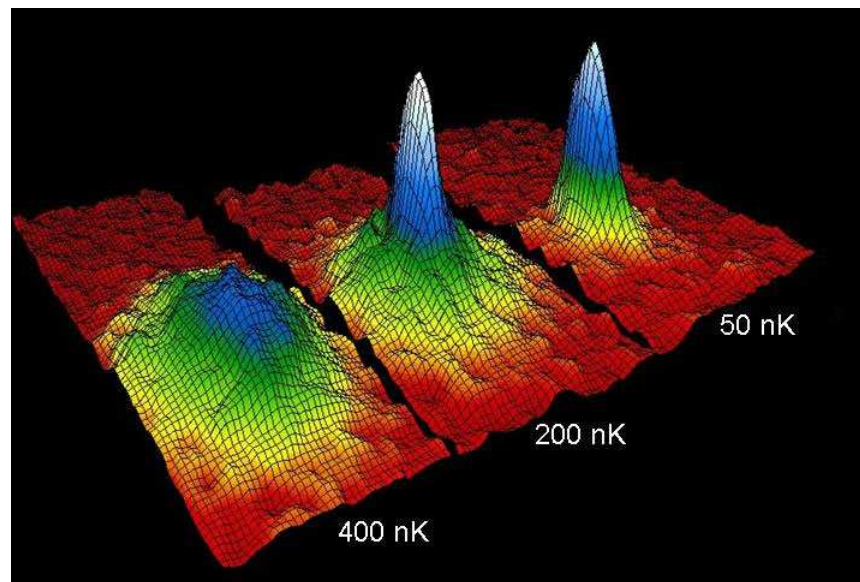
- **Atom trapping**  
magnetic traps  
optical traps
- **Laser cooling** (optical molasses)  
**Nobel Prize in Physics – 1997**  
“for development of methods to cool and trap atoms with laser light”  
**Chu, Cohen-Tannoudji, Phillips**
- **Evaporative cooling**

Ultracold atoms (cont.)

## Bose-Einstein condensation of atoms

$^{87}\text{Rb}$  atoms

Cornell and Wieman group, JILA, 1995



$^7\text{Li}$  atoms

Hulet group, Rice, 1995

$^{23}\text{Na}$  atoms

Ketterle group, MIT, 1995

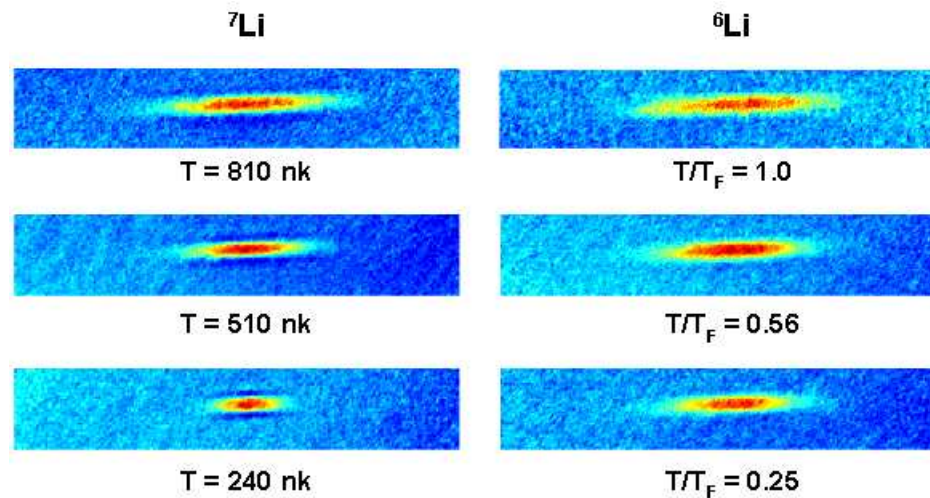
## Ultracold atoms (cont.)

## Degenerate fermionic atoms

$^6\text{Li}$  atoms

Hulet group, Rice, March 2001

sympathetic cooling by  $^7\text{Li}$  atoms



??

Ecole Normale, 2001

Ultracold atoms (cont.)

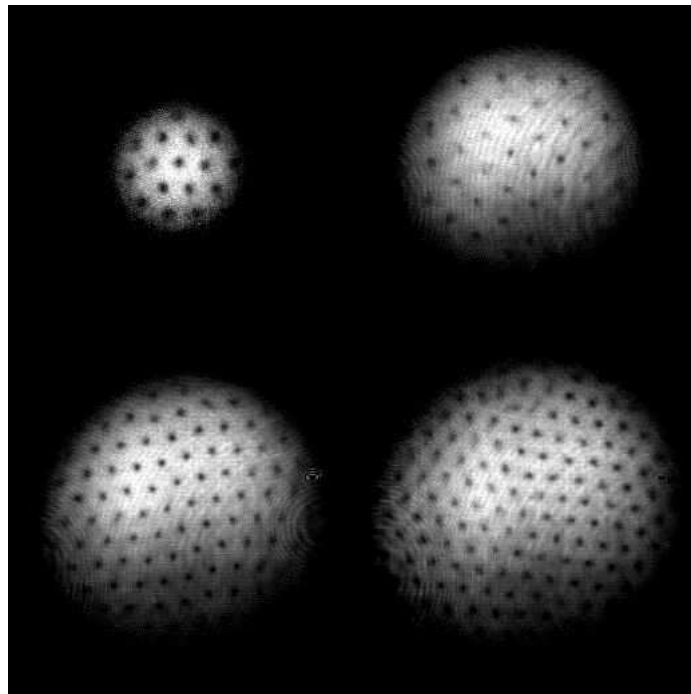
## Vortices in a Bose-Einstein condensate

$^{87}\text{Rb}$  atoms

Cornell group, JILA, August 1999

$^{23}\text{Na}$  atoms

Ketterle group, MIT, Feb 2001

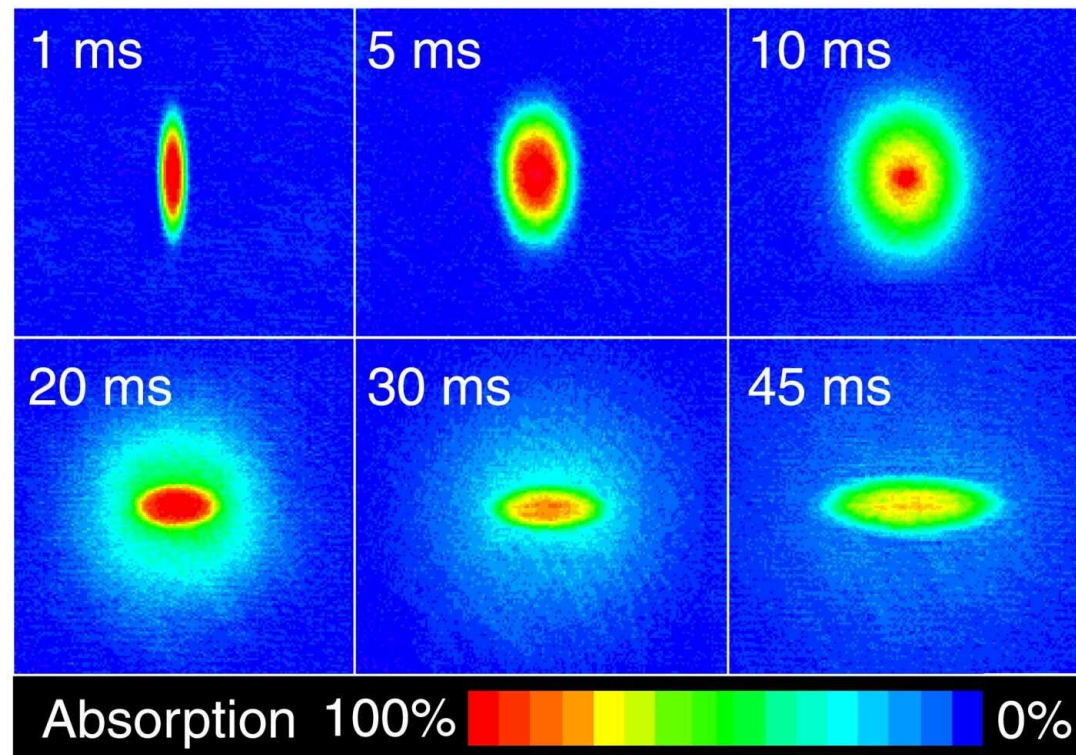


Ultracold atoms (cont.)

## Anisotropic expansion of a Bose-Einstein condensate

$^{23}\text{Na}$  atoms

Ketterle group, MIT



## Ultracold atoms (cont.)

### Interactions of ultracold atoms

are determined by scattering length  $a$

Low-energy cross section:

$$\sigma(E) \approx 4\pi a^2$$

Generic atom:

$|a|$  comparable to range set by interatomic potential

$$|a| \sim 10 - 100 \text{ \AA}$$



# Strongly-interacting Atoms

Strongly-interacting:  $|a|$  much larger than range  
set by interatomic potential

typical range\*:  $r_{\text{int}} \sim 10 - 100 a_0$

Strongly-interacting:  $|a| \gg 10 - 100 \text{ \AA}$

Atoms with large scattering length  
have universal properties determined by  $a$

“Universality of Few-Body Systems with Large Scattering Length”  
Braaten and Hammer, arXiv:cond-mat/0410417, Physics Reports

\*relevant range:  $r_{\text{int}} \sim (mC_6/\hbar^2)^{1/4}$ ,  
where  $C_6$  is coefficient in van der Waals potential:  $V(r) \longrightarrow -C_6/r^6$

## Strongly-interacting Atoms (cont.)

large scattering length requires fine tuning!

- Accidental fine tuning

$${}^4\text{He}: a \approx +200 a_0$$

$${}^6\text{Li}: a_t \approx -2160 a_0$$

$${}^{85}\text{Rb}: a_s \approx +2800 a_0$$

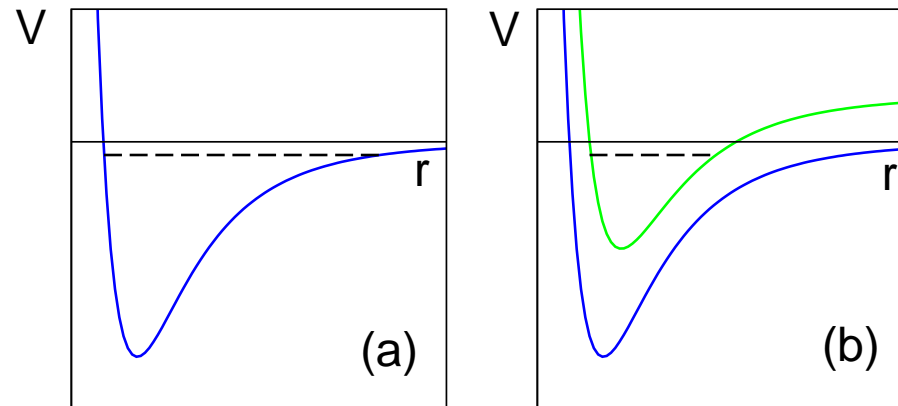
$${}^{133}\text{Cs}: a_t \approx +2405 a_0$$

- Experimental fine tuning

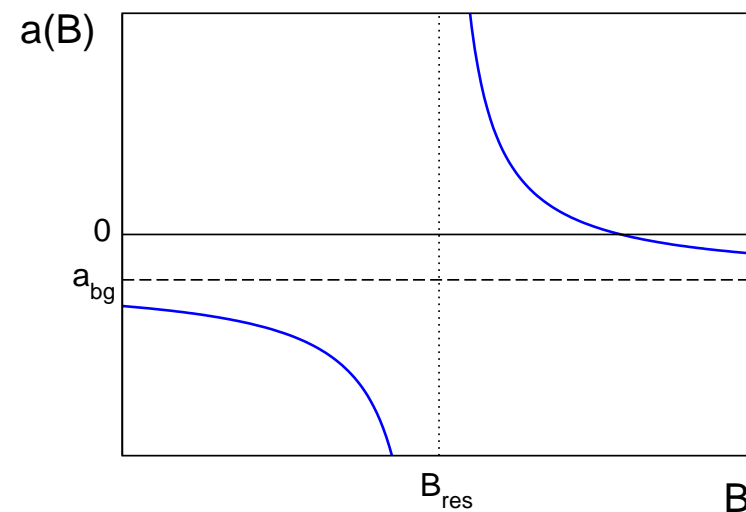
tune magnetic field to a Feshbach resonance

$$a(B) \approx a_{\text{bg}} + \frac{c}{B - B_0}$$

## Strongly-interacting Atoms (cont.)



Feshbach resonance: diatomic molecule in closed channel  
is tuned to resonance  
with 2 low energy atoms in open channel



## Strongly-interacting Atoms (cont.)

strongly-interacting atoms can be described by  
Local Nonrelativistic Quantum Field Theory

quantum field  $\psi_i(\vec{r}, t)$  for each type of atom  
and for each hyperfine spin state

$$\begin{aligned}\mathcal{L} = & \frac{i\hbar}{2} \left( \psi_i^\dagger \frac{\partial}{\partial t} \psi_i - \frac{\partial}{\partial t} \psi_i^\dagger \psi_i \right) + \frac{\hbar^2}{2m_i} \nabla \psi_i^\dagger \cdot \nabla \psi_i \\ & - g_{ij,kl} \psi_i^\dagger \psi_j^\dagger \psi_k \psi_l\end{aligned}$$

coupling constants  $g_{ij,kl}$

Natural scattering lengths:  $g_{ij,kl} \sim a_{ij,kl}$

Large scattering lengths: tune  $g_{ij,kl}$  nonperturbatively  
as functions of ultraviolet cutoff to get large  $a_{ij,kl}$

## Strongly-interacting Atoms (cont.)

Bosonic atoms in single **hyperfine spin state**  
with **large scattering length  $a$**

Universal 2-body properties:

- **Low-energy** cross section

$$\sigma(E) \approx \frac{8\pi a^2}{1 + a^2(mE/\hbar^2)}$$

- **Shallow** 2-body bound states (**dimers**)

$a < 0$ : none

$a > 0$ : one (S-wave), with binding energy

$$E_D = \frac{\hbar^2}{ma^2}$$

## Strongly-interacting Atoms (cont.)

Fermionic atoms in two **hyperfine spin states**  
with **large scattering length  $a$**

Universal 2-body properties:

- **Low-energy** cross section

$$\sigma(E) \approx \frac{4\pi a^2}{1 + a^2(mE/\hbar^2)}$$

- **Shallow** 2-body bound states (**dimers**)

$a < 0$ : none

$a > 0$ : one (S-wave), with binding energy

$$E_D = \frac{\hbar^2}{ma^2}$$

# Anisotropic expansion of degenerate Fermi gas

Thomas group, Duke, Oct 2002

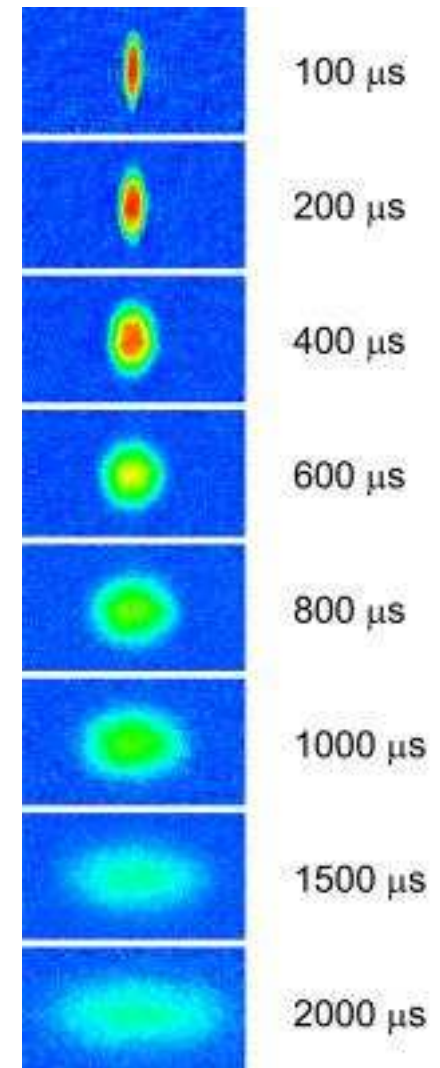
$^6\text{Li}$  atoms near Feshbach resonance  
and above  $T_c$  for superfluidity

## Strong interaction limit

$B = 910$  G:  $a \approx -\infty$   
anisotropic expansion

## Weak interaction limit

$B = 530$  G:  $a \approx 0$   
spherical expansion



## Strongly-interacting Atoms (cont.)

shear viscosity coefficient:  $\eta$

entropy density:  $s$

conjectured universal lower bound

Policastro, Son, and Starinets, April 2001

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi}$$

saturated by  $N = 4$  Susy-Yang-Mills with large  $N_c$  and  
strong coupling: perfect fluid!

Are strongly-interacting ultracold atoms  
a near-perfect fluid?

Gelman, Shuryak, and Zahed, Oct 2005



# Interaction energy of degenerate Fermi gas

Salomon group, Paris, March 2003

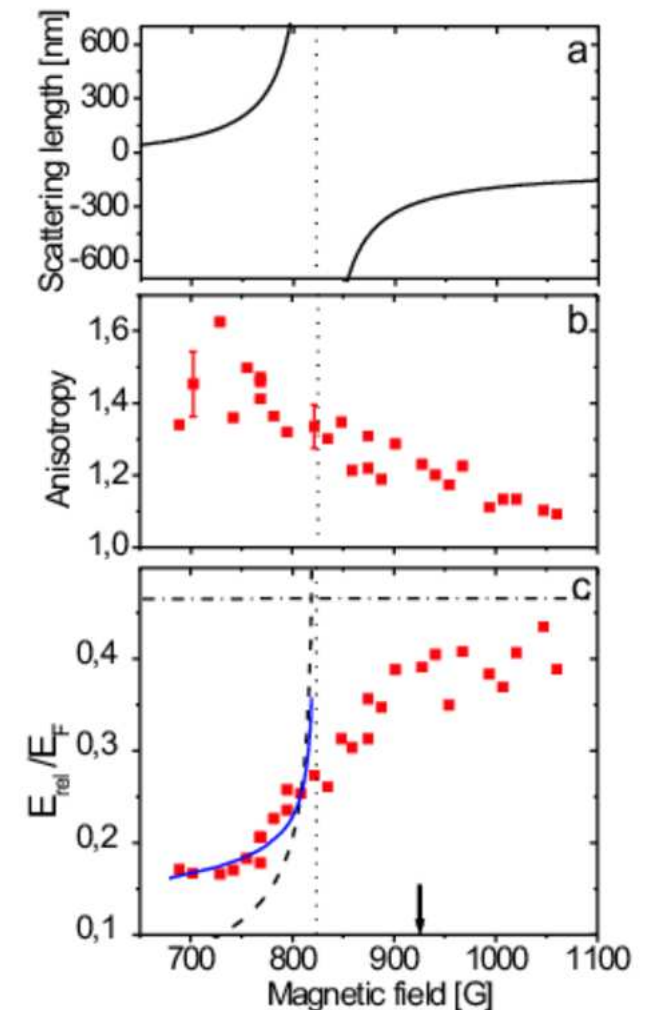
$^6\text{Li}$  atoms near a Feshbach resonance

interaction energy  
as a function of magnetic field

$$E_{\text{int}} \approx -0.3 E_{\text{kin}} \quad \text{at } a = \infty$$

smooth crossover

from BCS region ( $a < 0$ )  
to BEC region ( $a > 0$ )



# Thermodynamics of Unitary Fermi gas

- critical temperature for superfluidity?
- energy per particle at  $T=0$ ?

## Quantitative calculations

Carlson and Reddy (March 2005)

Bulgac, Drut, and Magierski (May 2005)

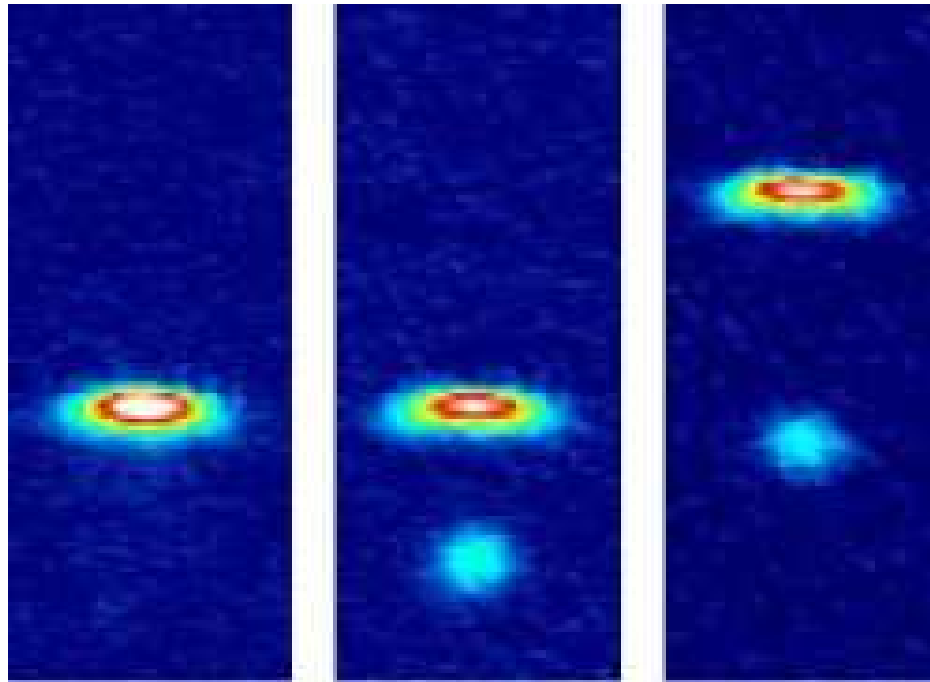
Lee (May 2005)

Burovski, Prokof'ev, Svistunov, and Troyer (Feb 2006)

Son (April 2006)

# Bose-Einstein condensate of diatomic molecules

Condensate of  $^6\text{Li}$  dimers      Grimm group, Innsbruck, Nov 2003



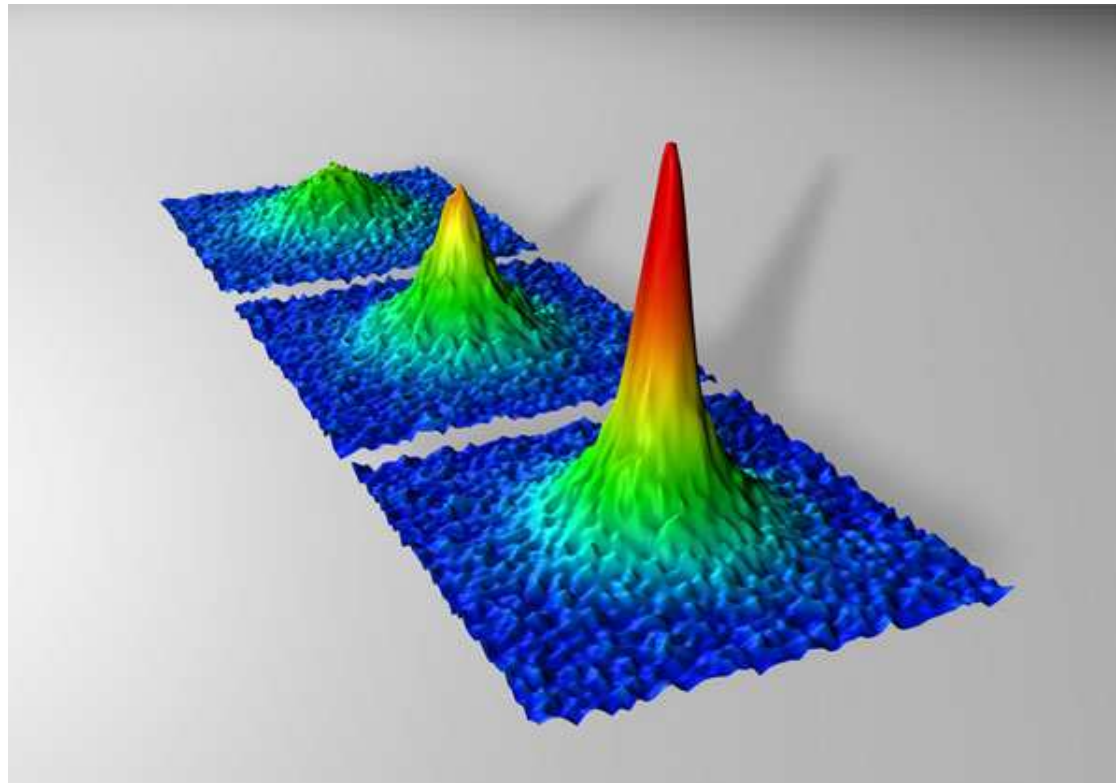
Condensate of  $^{40}\text{K}$  dimers      Jin group, JILA, Nov 2003

Condensate of  $^6\text{Li}$  dimers      Ketterle group, MIT, Nov 2003

# Condensation of Fermi pairs

$^{40}\text{K}$  atoms

Jin group, JILA, Jan 2004



cool atoms on BCS ( $a < 0$ ) side of Feshbach resonance  
then suddenly switch to BEC side ( $a > 0$ )

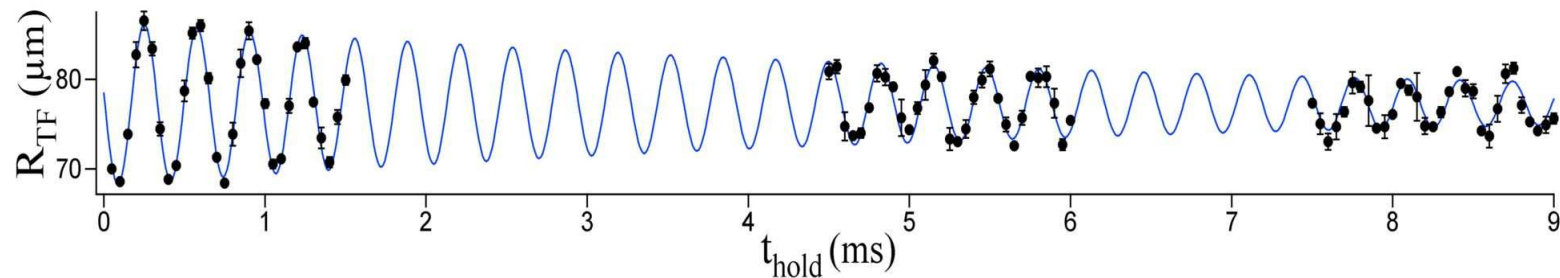
$^6\text{Li}$  atoms

Ketterle group, MIT, March 2004

# Collective modes in degenerate fermi gas

Thomas group, Duke, March 2004

radial size of cloud of  ${}^6\text{Li}$  atoms vs. time



long lifetime of oscillations

suggests that cloud is **superfluid**

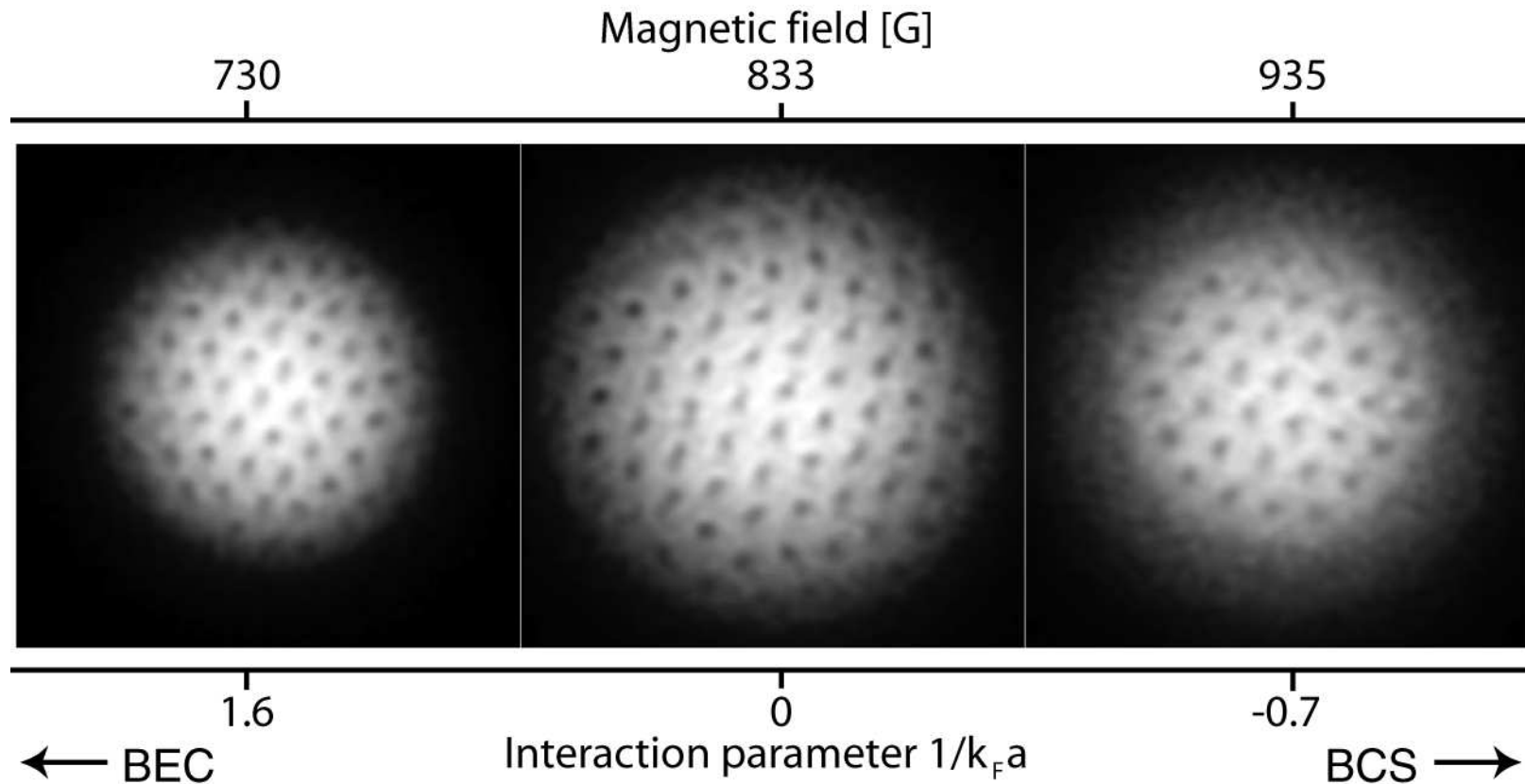
frequency in excellent agreement with prediction

for hydrodynamic Fermi gas with  $a = \infty$

# Vortices in degenerate Fermi gas!

Ketterle group, MIT, May 2005

strongly-interacting rotating cloud of  $^6\text{Li}$  atoms

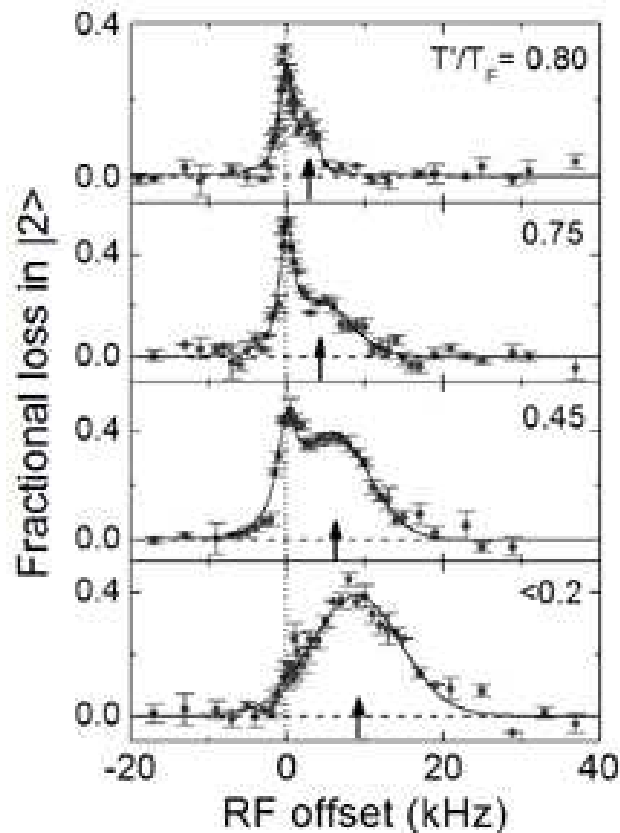


presented at  
Workshop on Strongly Interacting Quantum Gases,  
Ohio State University, April 2005

# Measurement of pairing gap in degenerate Fermi gas

Grimm group, Innsbruck, May 2005

strongly-interacting  ${}^6\text{Li}$  atoms



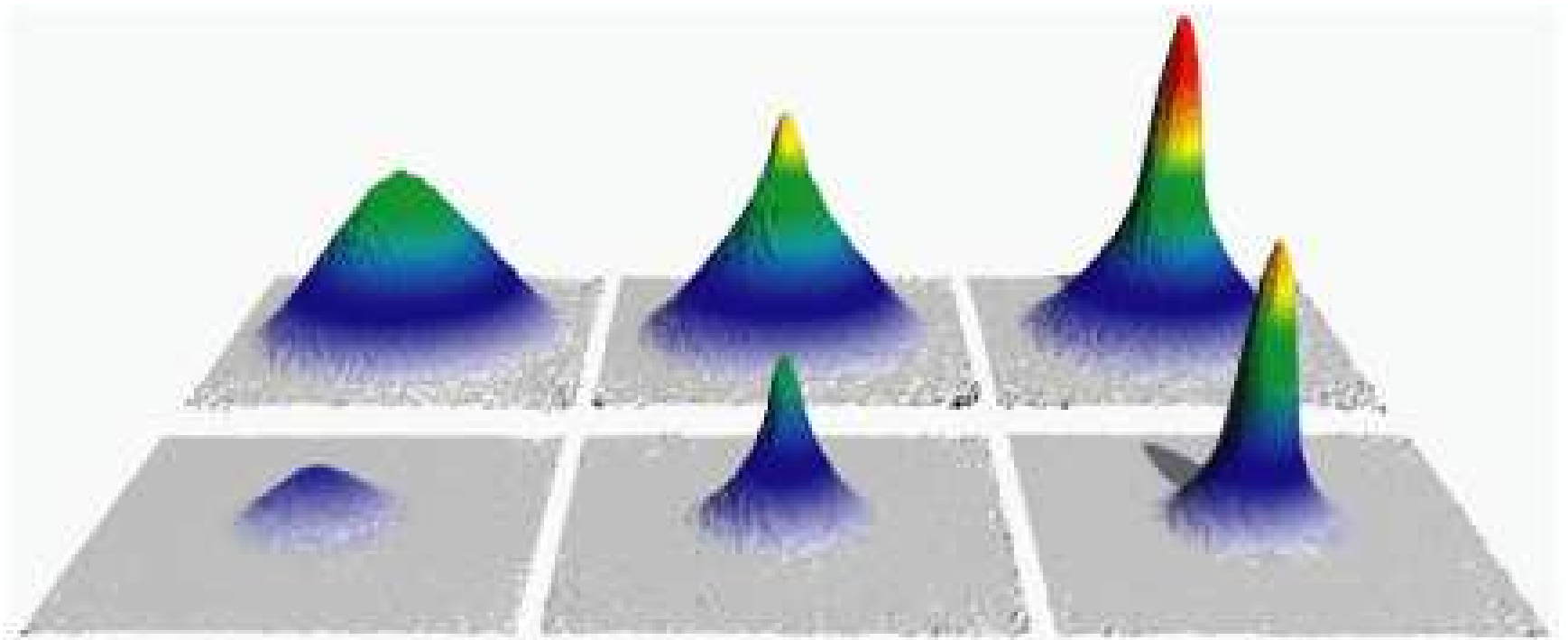
measure pairing gap using RF spectroscopy

# Fermion Superfluidity

with Imbalanced Spin Populations

$^6\text{Li}$  atoms in 2 hyperfine spin states

Ketterle group, MIT, Dec 2005



bottom row: majority spin component

front row: minority spin component



Bosonic atom with large scattering length  $a$

Universal 3-body properties:

- $a = \pm\infty$ : infinitely many 3-body bound states

binding energies :  $E_T^{(n)} = (1/515.0)^n E_T^{(1)}$

Efimov (1971)

- $a > 0$ : interference zeroes of 3-body recombination rate at

$$a = (22.7)^n a_{\min}, \quad a_{\min} = 0.32 (m E_T^{(1)} / \hbar^2)^{1/2}$$

Nielsen and Macek (1999); Esry, Greene and Burke (1999);  
Bedaque, Braaten, and Hammer (2000)

- $a < 0$ : resonant peaks in 3-body recombination rate at

$$a = (22.7)^n a_{\max}, \quad a_{\max}/a_{\min} = -4.88$$

Braaten and Hammer (2001)

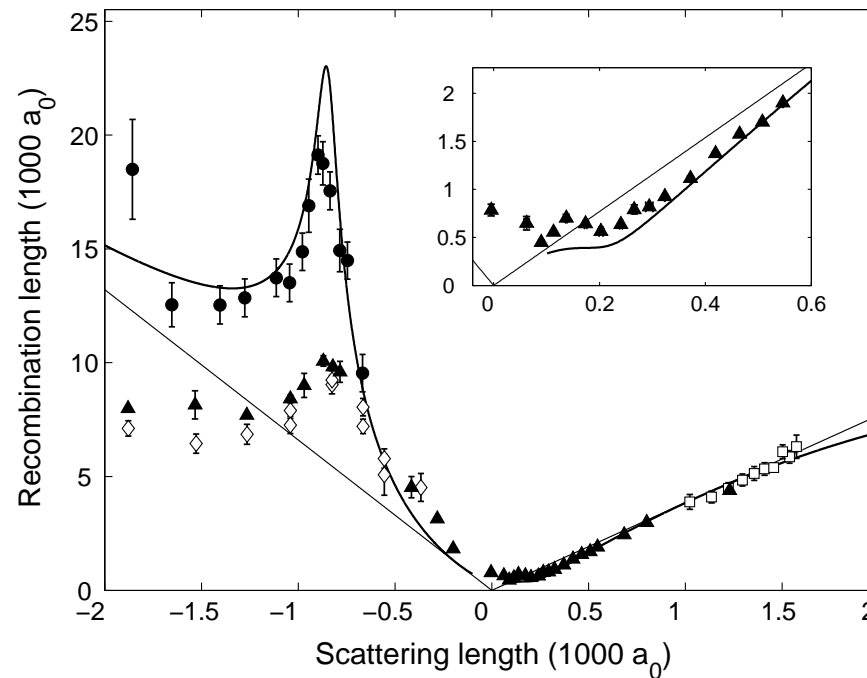
Discrete scaling symmetry:  $\vec{r} \longrightarrow (22.7)^n \vec{r}$

# Evidence for Efimov states

Grimm group, Innsbruck, Dec 2005

$^{132}\text{Cs}$  atoms at 10 nK

3-body recombination: atom + atom + atom  $\longrightarrow$  dimer + atom



resonance peak at  $a_{\text{max}} > 0$

minimum at  $a_{\text{min}} < 0$

ratio  $a_{\text{min}}/a_{\text{max}}$  agrees with universal prediction